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LOCKS AND LOCK-GATES

FOR

SHIP CANALS.

BY

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LOCKS AND LOCK-GATES FOR SHIP CANALS.

BY HENRY GOLDMARK, A.B., M. AM. SOC. C. E.

The problems of canal construction as a part of the Civil Engineer's work have within recent years assumed new and unexpected prominence. Several important canals for a navigation of the first-class have lately been completed and further projects of unparalleled magnitude are now under construction or the subject of serious discussion.

Among the large works recently finished abroad may be mentioned the Manchester, the North Sea-Baltic, and the Corinth canals, and the enlargement of the canal prism at Suez and Amsterdam. In America the most important waterways under construction or survey are the great Drainage Canal at Chicago now nearly finished ; the rival projects at Panama and Nicaragua, and the equally important plan for a canal of the first-class connecting the Great Lakes with tidewater.

All this activity is the more striking, because for more than a generation the rapid development of railroads appeared to have given a death blow to new canal construction, and many existing canals had suffered a decrease in their traffic or been entirely abandoned.

There were, however, good reasons for this temporary decline which was not due to any inherent weakness in canals as such, but rather to a mistaken public policy by which their great advantages were not properly made use of. The superior economy of transportation by water with vessels of proper design and in waterways of considerably size is not open to question. The modern freight steamer, both on the high seas and our own Great Lakes, carries freight at a cost much less than even the lowest railroad rates. The tonnage of the lake traffic, particularly, has of late years advanced by leaps and bounds.

It is, perhaps, impossible to reach the same high degree of economy in the case of canal and river channels, which are necessarily more restricted. But in canals of large cross section, using modern vessels propelled by power, the cost per ton mile should not be much greater than in open water. The real reason why our canals have decreased so much in relative importance lies in the fact that in size, in construction, and especially in the nature of the boats used on them, they are many years behind the times and represent a phase of development long past in all other departments of transportation. When operated in competition with the highly developed railway systems, embodying the latest improvements of modern engineering, it is not to be wondered at that they have lost most of their former importance.

The only way in which canal navigation can be revived is to put it, as nearly as feasible, on the same footing as navigation in lakes and large rivers, by using large vessels, equipped with modern machinery, in channels of sufficient cross-section to keep the resistance to the movement of the vessels within economical limits. It goes without saying that canals of this description are very expensive to construct and maintain. There will, therefore, be but few locations on which the volume of the traffic will be sufficient to warrant their construction, and we may expect that but few canals will be built in the future, but they will be works of strictly the first class.

To the constructing engineer canal building offers many problems of great interest. The location of the canal, both from a commercial and a strictly engineering standpoint, requires careful study, while the excavation of the channel offers a field for introducing new and ingenious methods for handling earth and rock work on a large scale. The hydraulic questions involved, such as seepage, evaporation, problems of water supply, the flow of water in open channels, etc., are all interesting as matters of theory and offer a rich field for experimental research.

In this paper it is not proposed to take up any of these topics, but to confine it to the subject of canal *locks*, not only because they are the most important structures in canal construction, but also because they have not been adequately treated in American engineering text books.

GENERAL DEFINITIONS.

A canal lock may be defined as a structure which enables vessels to pass from a body of water to an adjacent one which is at a different level. As usually built, it consists of an enclosed basin or chamber provided with gates by which it may be shut off at either end so that it can be put in communication alternately with the upper and lower levels. The method by which boats are passed through a lock is simple, and readily understood. Besides the ordinary canal lock, various other means for overcoming differences of level in canals have been proposed at different times for at least 100 years past. Among these may be mentioned inclined planes and mechanical lifts acting vertically. A few inclined planes have been in use on small canals both in America and Europe for many years. Of vertical lifts a large number of projects have been worked out on paper, but only four of these have been built and are now in use. They are the hydraulic lifts at Anderton, England; Les Fontinettes in France, and La Louviere in Belgium, and the floating lift, so-called, at Henrichenburg in Prussia. The largest of these is the last named, which is 230 feet long, 28 feet wide, with a draft of water of 8 feet. The amount of lift is 52½ feet.

The operation of these lifts, the oldest of which has been in use for over 20 years, is quite satisfactory. Their principal *raison d'être* is the saving in water which they accomplish as compared with ordinary masonry locks. They are certainly of much interest, and in special locations their use will probably be more general in the future. The locks are, however, at best the most vulnerable portion of a canal system, and engineers may well hesitate before putting a more complex mechanism in place of the simple and massive masonry lock.

HISTORY.

The invention of the canal lock is one of the few great discoveries by which civilization has been measurably advanced. It alone has made it possible to navigate many important rivers and to carry canals over considerable elevations where a single level canal would be out of the question. The credit for building the first lock is claimed by both Holland and Italy, but the evidence as to time and place is conflicting. While in the plains of Northern Italy, the navigable canal is the outgrowth of the shallow irrigating ditches used from time immemorial, the Dutch canal for boats has developed from the channels required to drain the low lying fields or polders. In both countries simple sluice or head gates were built long before the enclosed lock with enclosed chambers. Such gates are sometimes used for navigation and are often confounded with true locks by the earlier writers. The first clear and distinct description of a lock with an enclosed chamber is said to have been given by Leona Battista Alberti in his book entitled "De re Aedificatoria," a copy of which he presented to the Pope Nicholas V. in 1452. Simon Stevinus, the celebrated Dutch scientist, also gives a good account of a canal lock in a treatise published in 1618.

By other writers it is claimed that the first lock was built in 1481 near Padua in Italy, while the advocates of Dutch priority feel confident that true canal locks were in use in the Netherlands before 1250. It may be added that the common canal lock is frequently called the *Visconti* lock from its alleged inventor, while by others the laurels of Leonardo da Vinci, already so ample, are increased by ascribing the discovery to the great painter. The exact date is, of course, not very important. It is of interest, however, to note that lock building as well as canal construction generally, antedates the establishment of our profession by several centuries. In hydraulic works of all kinds, many successive generations had accumulated a large amount of practical experience long before the civil engineer, as such, had come into being. In canal work, a high degree of perfection was reached at least 150 years ago. Faulty methods in construction and operation had been gradually eliminated by the severe test of time and experience so that the forms then in use have been followed pretty closely, at least for small canals, down to the present day. Within the past fifty years many large locks have been built, but the principles of their construction are essentially the same as those followed in the older and smaller works.

Although the ordinary canal lock has often been criticised on various grounds, it cannot be denied that it has proved itself in practice an extremely satisfactory piece of mechanism. It is simple and durable, requires few repairs and is inexpensive in operation.

CLASSES OF LOCKS.

According to their location, locks may be divided into two general classes:

(1) Locks in inland canals and canalized rivers.
(2) Locks in maritime canals and harbors.

In the first class, the difference of level to be overcome is due to the configuration of the ground which makes it necessary to divide up the waterway into a series of pools or reaches at different levels. The "lift" in this case is practically constant and the water pressure against the gates of the lock always acts in the same direction.

On the other hand, in the locks used in harbors and in canals communicating with the ocean, the difference of level is due to the tides and in certain cases to wind action. In the North Sea–Baltic Canal, for instance, there is a complete lock at the east end of the canal which is in use only about 25 days in the year, at times when a strong east wind from the Baltic piles up the water in the outer harbor.

The principal use of locks in harbors is for closing dock entrances where the range of the tides is considerable. This is the case on the coasts of England and Germany and on the Atlantic coast of France. The difference between high and low tide is rarely less than 15 feet, while in some localities, such as the ports in the Bristol Channel, it reaches 44 feet at certain times in the year. In these harbors vessels are loaded and unloaded in enclosed basins surrounded by quay walls in which the water is kept approximately at a constant level. These basins have narrow entrances, closed by one or more gates. In some of the docks, especially those of earlier construction, there is no enclosed chamber so that the lock reduces to a mere pair of gates in the entrance channel. These gates are open for an hour or so at high tide and all vessels must pass in and out at this time. When the tide in the outer harbor begins to fall, the gates are closed and keep the water in the dock basin from running out. In order to provide against exceptionally high tides in the outer harbor, another pair of gates is usually added which are built so as to support water pressure acting from the outside. A further modification where the range of tide is great is the introduction of a "half tide lock" with a second pair of gates so that the pressure on each of them is reduced.

The limited time to which the traffic is confined in this form of dock entrance is objectionable and many modern English docks are provided with complete locks having enclosed chambers so that vessels can be locked through between the outer harbor and the docks at all hours. At high tide the gates are left open for some time and the larger vessels usually come into the dock without locking.

The construction of these harbor locks is almost exactly identical with the locks on large ship canals. In the leading ports of Great Britain, a large number have been built in the last fifty years. In Liverpool alone there are more than 100 pairs of lock gates for openings varying from 40 to 100 feet. As but few large ship canals have so far been built, it is to the experience gained in building these large dock gates that we must look for guidance in designing similar works.

DIMENSIONS.

In designing a complete canal lock, the first points to be fixed are the proper dimensions. These are the length, the width, the depth of water on the sill and the lift or difference of level between the water above and below the lock.

The width and length, and the depth on sill are commonly the same for the whole canal and depend on the maximum size of vessel employed. On the canal proper, it is necessary to make the prism very much greater than the cross section of the vessel, say from 4 to 6 times as great, so as to reduce the resistance to motion through the water to an economical amount. In the locks this is unnecessary. An excessive size involves waste of water, increases the time required to operate the lock and greatly increases the first cost. In some cases where the traffic is very heavy, locks have been built wide enough to allow two ordinary vessels to be docked side by side and long enough to take in several of them, one behind the other. The new American lock at Sault Ste. Marie, which is 100 ft. wide and 800 ft. long, is a so-called "fleet lock" of this kind. The wisdom of this design is doubtful. As the width and length of lake vessels is constantly increasing, it will not be very long before all the older and smaller vessels will go out of service, so that the 100 ft. lock will not be wide enough to take in two of the vessels side by side nor long enough to allow them to enter "tandem." In that event the large dimensions of the lock will be worse than useless. The Canadian lock at the Sault, finished in 1895 is anly 60 ft. wide, but 900 ft. long and appears better adapted to the demands of traffic.

The probable size of vessels in the future is not easy to foresee and the dimensions to be adopted for designing locks for large ship canals will vary greatly according to individual judgment. Some thirty years ago the largest vessels were steamers with paddle wheels that projected a considerable distance on either side of the hull proper. To provide for these, several locks 100 ft. wide were built in the Liverpool and Havre docks. These are now far wider than necessary. At present few merchant vessels are wider than 60 ft., although a few of the largest exceed this limit and the Freidrich der Grosse is 68 ft. wide. War vessels have somewhat greater beam; the Iowa of the U. S. Navy is 76 ft. wide over all.

The locks on the North Sea-Baltic Canal are 82 ft. wide, while the new locks at Bremerhaven are to have a clear width of 92 ft. in accordance with the request of the North German Lloyd Steamship Company. On the Manchester Canal 80 foot and 65 foot locks are used although a narrower lock is built at the side for small craft. The proposed locks for the new Panama Canal are to be 59 and 82 ft. wide and about the same widths will probably be adopted at Nicaragua.

The depth of water on the sill of the lock, should equal the maximum draft of the boats with an additional clearance of 1½ to 2 feet. The "lift" of a lock is its most important feature. If the width may be compared to the "length of span" in a bridge, the lift is analogous to the loading to which the bridge is subjected. The lift or difference of level is fixed by topographical configurations, though in many cases the location of the canal is affected by the amount of lift which can safely be used. The inferior limit of the lift, in a lock may be 1 ft. or even less. The upper limit has not yet been reached. Very few locks with lifts exceeding 20 to 25 feet have ever been built. The greatest lift known to the writer in an inland canal lock is 30 ft. This lift is used at the new locks in St. Denis Canal in France. In the Avonmouth dock at Bristol, England, the range of the tide is nearly 44 ft. and the strength of the gates is calculated for a head of 45 ft. This lock was built nearly thirty years ago and though the gates are of timber, their operation has been entirely successful.

The question whether lifts as high as 40 or 50 feet are advisable must be studied carefully for each separate case and will depend on the supply of water, the density of traffic and other considerations as well as on the structural difficulties involved. During the past year the writer has been engaged in the design of locks of various lifts up to 50 feet. So far as his plans have been matured, they show no reason why lifts of 45 or 50 feet could not be successfully used on locks as wide as 80 feet.

Such great lifts will seldom be needed as the topography of the country passed through is almost always such as to make the majority of locks of moderate lift. Even where a concentration of the locks at a few points might otherwise be advantageous, this can rarely be done without flooding too large an area of valuable land. For this reason the opinion sometimes expressed that the adoption of mechanical locks which permit the concentration of the lift at a few points will always result in economy, is a mistaken one.

CONSTRUCTION OF LOCK WALLS.

The construction of a lock may be divided into three parts.

(1) The foundation, the side walls and the floor which are generally built of masonry.

(2) The culverts and valves for filling and emptying the lock, with the mechanism for operating the valves.

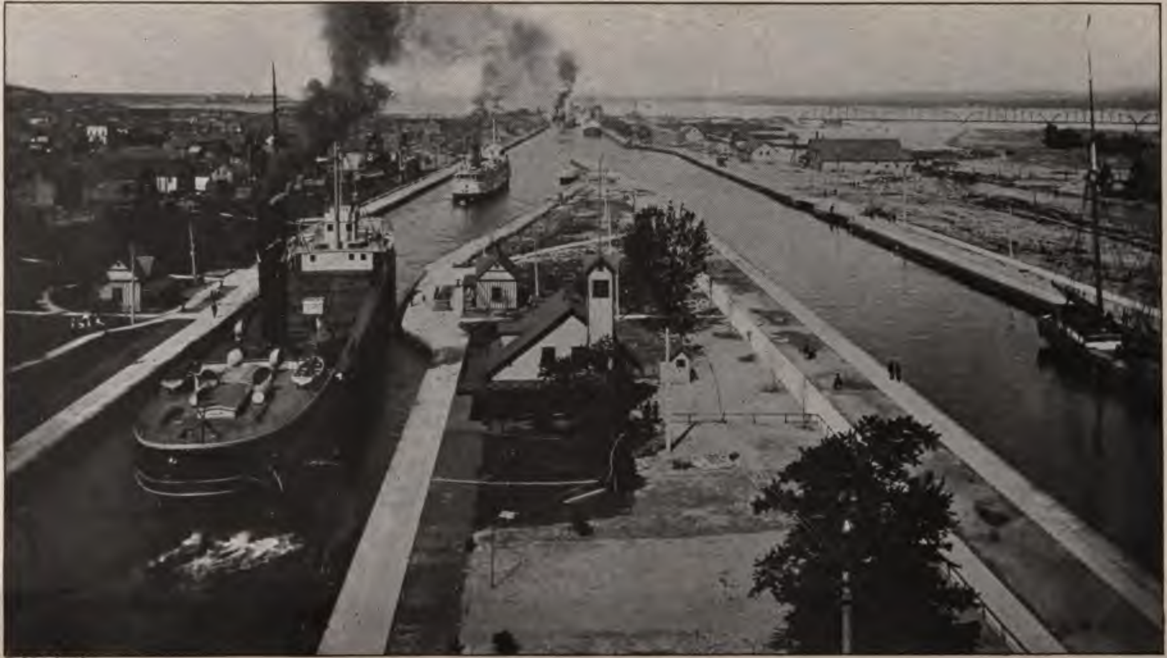
(3) The lock-gates and the machinery for moving them.

As in most structures, the nature of the foundation encountered affects the difficulty of construction to a high degree. Fortunately in inland canals, the locks can often be located on a solid rock bottom. In the case of harbors, on the other hand, rock is rarely encountered and in many cases the bottom is extremely soft. The successful operation of the gates requires that the side-walls and sill should remain almost absolutely true to their original lines. The difficulty of securing this result is very much greater than that encountered in building an ordinary quay wall. No general directions can be given as to the best choice of foundation in any given case. When the bottom consists of a rather firm sand or clay, it is usual to cover the entire site with a layer of concrete of sufficient thickness to support the upward thrust of the water which may tend to litt it. This layer of concrete is laid in the dry when this is feasible, but must usually be deposited under water. The side walls are built on this foundation and the portion between the walls forms the floor of the lock. When the bottom is softer and more variable, piling must be resorted to, at least under the side walls, so that the weight of the walls may not tend to crack the floor. The problem of dimensioning the side walls and the floor when the bottom is soft is extremely complicated.

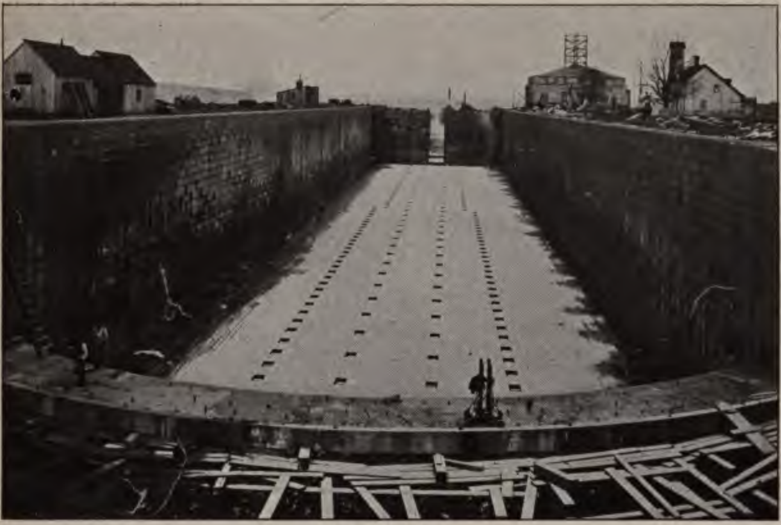
When built on solid rock, a lock wall can be designed according to well understood rules in the same way as a retaining wall. Each wall acts separately and its weight is carried by the rock bottom immediately below it. The forces tending to overthrow the wall are the earth pressure behind it, to which must be added a certain amount of water pressure varying with the permeability of the back filling. In this calculation the lock is, of course, supposed to be empty and the ground water to stand at its highest level.

When designing a lock to be built on a soft bottom, we cannot calculate the strength of each wall separately but must consider the entire cross section of the lock, *i. e.*, the two side walls and the concrete floor as a whole. This section is subjected to a variety of forces, viz.: the earth and water pressure on the side walls, the upward pressure on the bottom of the floor and the walls besides the weight of the masonry and of the water in the lock. The magnitude and distribution of the upward reaction of the bottom cannot be exactly estimated. It is possible, however, to make a graphic analysis and draw a line of pressures in the walls and floor under various hypotheses. By comparing the conclusions to be drawn from this analysis with practical experience in locks built on a soft bottom, much assistance can be gained in proportioning new structures. With the usual proportions the line of pressure at the middle of the floor is quite eccentric. This shows the existence of a considerable bending moment which would tend to crack the floor at the top. Such longitudinal cracks have actually occurred in a number of harbor locks at the very points indicated by the theoretical analysis. They are not necessarily of a destructive character and after they have been closed with concrete are not likely to give much further trouble. The structure after fracture is in a new position of equilibrium corresponding to a new distribution of pressures on the bottom.

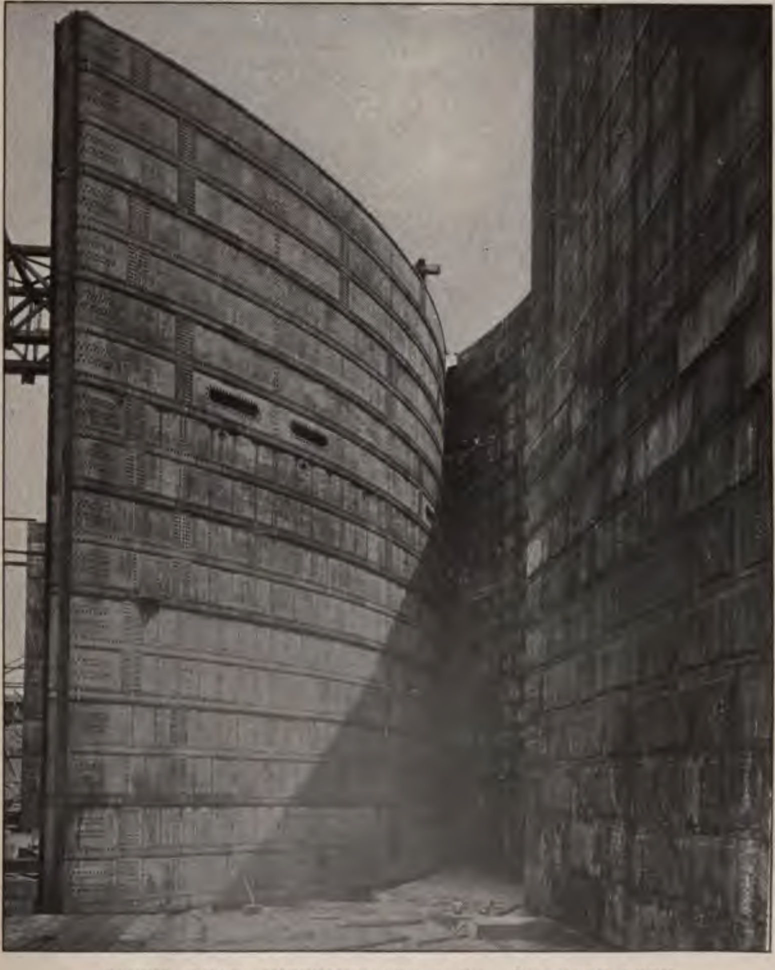
Laying concrete under water is always somewhat unsatisfactory. In



ST. MARY'S FALLS CANAL.



800 FOOT LOCK—ST. MARY'S FALLS CANAL.



SOUTH LEAF—INTERMEDIATE GATE. 800 FOOT LOCK.

building the large locks at Holtenau, on the North Sea-Baltic Canal, a simple but elegant method was used for lowering the ground water level and excluding the water from the lock pit. Three wells, 12 ft. in diameter, were sunk by compressed air to a depth of about 15 feet below the bottom of the pit. They were placed close to and just outside the lock at three of its corners. By pumping from these wells with centrifugal pumps for a period of 15 months, the water level over the entire lock was lowered so that the foundation could be built entirely in the dry.

Compressed air caissons and open wells sunk by dredging have also been used for the foundations of harbor locks. The method used is practically the same as that employed for bridge piers. The locks at Toulon, Dieppe and some other French ports were built with compressed air foundations, while the Bordeaux lock was founded on open wells. In the latter case, the close proximity of large warehouses was the reason for chosing this method.

The material used in lock walls is almost always masonry, but floors of timber construction are not unusual even in large locks. Cut stone masonry is generally employed, though rubble with an ashlar facing is not uncommon. Of late years some locks have been built entirely of concrete. Among these are the fine locks recently completed by the U. S. Government on the Hennepin Canal in Illinois. The writer has also had occasion to examine the masonry recently built for the new guard gates in the St. Mary's Falls canal. This masonry consists of a rich concrete without any cut stone and presents a very good appearance. The gates are of timber and span a clear opening of 108 ft. This is a greater width than any known to the writer elsewhere.

The masonry at the ends of a lock must support the pressure of the gates. The walls at the ends are necessarily thicker than the side walls of the chamber and must be built with extreme exactness so as to fit the gates. Their details will depend on the style of gate used.

The construction of the masonry is further complicated by the necessity of inserting culverts for the filling and emptying of the lock and also of tunnels for the cables that move the gates and the pressure pipes connected with the operating machinery.

ARRANGEMENTS FOR FILLING AND EMPTYING THE LOCK.

Three different plans are in use for this purpose.

(1) Valves in the upper gate.
(2) Side Culverts in the lock walls.
(3) Culverts under the floor of the locks.

The first plan has the merit of simplicity and is generally used in small locks. The openings are rectangular and placed as low as possible in the gates so as to act with the largest possible head. The valves are simple sluice gates operated by hand from the top of the gate. Such openings weaken the gate where the water pressure is greatest. Another objection is the fact that the water rushes in with much velocity and tends to break the cables of vessels in the lock. Furthermore the time required to fill a large lock by valves in the gates is excessive. For this reason, such valves are supplemented or replaced in most large locks by culverts in the side walls or under the floor. The latter arrangement can be conveniently adopted only in case of a rock foundation, to which the floor system can be bolted down to resist the upward pressure of the water, tending to lift the floor when the culverts are filled. The most important examples of such culverts are found in the three great locks at Sault Ste. Marie. In all of these the water is admitted through large rectangular culverts under the floor. They are about 8 ft. square and connect with the lock chamber by a large number of openings along the bottom of the lock. The culverts run side by side and are built of solid timbers. There are two culverts in the smaller American lock, six in the larger and four in the Canadian lock. The head is about 19 feet. The largest lock is filled in about 11 minutes, using four culverts only.

Side culverts are general in the larger European locks, such as those in the Manchester and North Sea-Baltic canals. There is a culvert in each wall about twice as high as it is wide. In the Manchester Canal the size of the culverts is 6 × 12 feet. They discharge into the lock by lateral openings.

In connection with culverts, three classes of valves are used, viz.: Slide valves, butterfly valves and cylindrical valves. The first class are rectangular and may be built of either metal or wood. It is desirable that they should move with little friction and be as nearly water tight as possible. On the Manchester Canal the Stoney sluice gates are very successfully used, in which the friction is largely reduced by a system of roller bearings. In the North Sea-Baltic Canal a similar sliding gate built of timber was adopted. In American locks butterfly valves revolving on a central axis are common. They are simple in design and durable and require but little power to operate them. The only objection to their use is the excessive consumption of water, as they cannot be made with a tight fit. This precludes their use where water is scarce.

Cylindrical valves are in use on many French canals and have been proposed for the enlarged Erie Canal. They consist of vertical steel cylinders resting on a conical seat, and are raised vertically to admit the water through an annular orifice. While these valves have many good features they are quite expensive as the amount of water that can pass through any one valve is comparatively small. Valves are generally operated by power, the machinery being combined with that for moving the gates.

LOCK–GATES.

Although they represent a relatively small part of the total cost, the gates are more complex in construction than any other part of the lock, and on their correct design its successful operation will largely depend. Considered merely as structures, they present an interesting field in the theory of stresses and in practical designing.

Every lock with an enclosed chamber must have at least two gates, one at each end. Besides this an intermediate gate is frequently added which permits the working length of the lock to be shortened so that smaller vessels can be locked through more quickly and with less waste of water. Quite generally, too, a guard gate is built at either end to allow the entire lock to be laid dry for periodic examination and repair.

Lock gates, whatever their detailed design, are really movable dams, and when closed support the pressure of a considerable head of water. The standard form used in the great majority of cases is the mitering gate. This consists of two leaves, each turning on a vertical axis like an ordinary door. When closed the leaves meet at an obtuse angle, the so-called toe-posts abutting against each other in the middle of the lock, while the bottom of the gate rests against a continuous sill. When in this position the two leaves act as an arch, which conveys the water pressure to the side walls. The fitting of the gates against each other and the sill is difficult to make and maintain uniform at all times. A bad fitting may interfere with the proper working of the gates, and also causes the stresses in the different members to be somewhat uncertain.

For these reasons among others, many substitutes for mitering gates have been proposed and some of them carried into execution. The more important of these forms may be briefly referred to.

(1) The single leaf revolving gate. This consists practically of one leaf of a mitering gate long enough to reach across the lock at right angles; the gate is supported on the bottom and both sides and acts as a girder or truss instead of an arch. The single leaf is, of course, heavier than the separate leaves of a mitering gate for the same open-

ing. It requires much more power to move it and also shortens the available length of the lock which can be occupied by vessels. The cost is about the same as for double leafed gates. Single leafed gates have of recent years been built in France up to 50 feet in length.

(2) The "Tumble" gate which also spans the canal with a single leaf, but revolves on a horizontal shaft fixed at the bottom of the lock. This form has been used in some of the Erie Canal locks for many years.

(3) Sliding Gates. Gates of this kind have been built in different English and continental harbors and in this country in connection with the Davis Island Dam in the Ohio river improvement. The foreign gates are of iron with closed air chambers, while the Davis Island gate which spans an opening of 110 feet is of timber framing. These sliding gates when closed, act as trusses supported by the side walls and the sill. They are opened by moving them sideways at right angles to the lock into a recess constructed in the masonry wall on one side.

(4) Pontoons. Pontoons are sometimes rectangular gates like the sliding gates just referred to, although they may also be built having the curved outlines of an ocean vessel. They are floated across the lock entrance and are sunk into position by letting water into tanks provided for the purpose. When the lock is opened they are moved into recesses in the wall. Pontoons are used generally in dry docks, but are not well adapted for ordinary canals where rapid and frequent moving of the gates is required. The same may be said of the sliding gates although the latter if properly designed and fitted with a good moving mechanism would probably give good satisfaction in canal work.

The ordinary mitering gate has, however, in the writer's opinion, so many strong points in likeness, durability and facility of movement that it is likely to hold its own even for large locks.

MITERING GATES.

Mitering gates are built of all sizes from the great gates spanning an opening of 100 feet down to the smallest guard gates. The material used in their construction is timber or iron or a combination of the two. For small gates, timber is in every way preferable as the first cost is less, repairs are more easily made and there is no difficulty in designing gates of simple construction using timbers of small scantling and length. A number of small iron gates have been built in different countries, but the concensus of opinion among the Engineers directly in charge of canals seems to be averse to their general adoption.

The general use of steel in bridges and ships, makes large wooden lock gates seem somewhat out of date. Metal would appear to have great advantages as in other engineering structures. Large iron gates, have as a matter of fact, been in use for over fifty years, the first wrought iron gate having been built for a 60 ft. dry dock entrance in the Brooklyn Navy Yard about 1850, while about the same time similar gates were constructed by English engineers at Sebastopol, Russia. It has never been denied that these and later iron gates have given perfect satisfaction.

It is true, nevertheless, that many English and American engineers of great experience in lock work remain strongly prepossessed in favor of timber gates. In England even at the present day, about half of the new gates are built of wood. In the Manchester Canal Greenheart timber, a very durable wood, brought from British Guiana was used exclusively in the 54 gate leaves built, although the cost was much greater than that of iron gates. Some of the larger American gates such as those in the new Canadian lock at the Sault are also built of wood.

Apart from natural conservatism, the reasons which make for wooden gates are, their greater lightness which makes them easier to move and still more the ease with which they may be repaired in case of a collision. Such accidents are always possible, although they are rare. It does not seem to the writer, that this contingency is sufficiently probable to make it wise for us to give up the great advantages of steel gates.

DETAILS OF CONSTRUCTION.

A mitering gate consists of a skeleton or *frame* and a *water tight* sheathing. The frame may be arranged in different ways, but there is always a heel or quoin post close to the masonry, a toe or mitre post at the other end of the leaf and two horizontal girders, one at the top and another at the bottom of the gate. Besides this there are usually a number of intermediate horizontal girders forming a series of arches or rafters carrying water pressure. In a few gates, vertical girders which bear against the top horizontal girder and the bottom sill take the place of the intermediate horizontals. The weight of the gate is supported on a vertical pivot fastened to the bottom of the quoin post, while at the upper end of this post, there is an anchorage which extends into the masonry wall. A roller traveling on a circular track on the bottom of the lock has in the past been quite generally used at the outer end of large gate leaves. This relieves the pivot and anchorage of much weight but makes distribution very uncertain. The disadvantages of rollers have led to their gradual abandonment.

TIMBER GATES.

The sheathing is always made of planking with calked joints. The posts consist of one large timber or are built up of several pieces. The horizontals differ in construction according to the size of the gate. For moderate spans straight horizontals made of a single timber can be used, but for larger gates built-up trusses must be employed. Where long timbers can be had bowstring girders with iron tie-rods or tie-beams of wood are probably the best forms to be adopted. As examples of such girders, the old gates for the 100-foot dock entrances at Liverpool and Havre and the Weitzel lock at the Sault (60 feet wide) may be referred to. The gates in this last lock have been renewed during the past winter. They were designed by Mr. Alfred Noble, M. Am. Soc. C. E., and completed under his care in 1881. The iron rods, pivots, etc., were found to be in perfect condition and have been used for the new gates.

When long timber is difficult to obtain, the horizontal girders may be built up of several short lengths framed between vertical intermediate posts and bolted to re-inforcing timbers. Many English gates are built in this way.

IRON AND STEEL GATES.

Iron or steel gates like timber gates consist of a frame and a sheathing, both of metal. The cushions at the quoin and mitre posts and the sill where a water-tight closure is required are usually made of wood.

The design of a steel lock-gate, like that of any other structure, is largely dependent on the forces which it has to resist. These will be different when the gate is opened and when it is closed. When open the gate exerts a horizontal pull on the anchorage while its weight rests on the pivot. These forces must be transmitted through the gate frame and are readily analyzed.

When the gate is closed the water exerts a horizontal pressure, which is transferred by the gate to the side walls and sill of the lock. The magnitude of this pressure is easily determined, being at each point equal to the hydrostatic head. The upper gate is most strained when the lock is entirely empty. The pressure increases from zero at the top to a maximum at the bottom and may be represented by a triangle.

In the lower gate it is zero at the top increasing uniformly to the level of the lower pool and from that point is a constant to the bottom of the gate. It may be represented by a trapezoid.

The gate can be designed to stand this pressure in various ways. The most common form consists of a series of horizontal girders spaced in an approximately equal manner and fastened securely to the quoin and mitre posts. They are further held in place by vertical frames, intermediate between these posts, which add greatly to the stiffness of the gate. The sheathing consists of plates riveted to the horizontals and calked at all joints to secure water-tightness. This sheathing is required only on one side as far the function of the gate as a dam is concerned. It is a very general practice, however, to place the covering on both sides, forming a series of air-tight compartments, the flotation of which relieves the pivot and anchorage of weight and makes the gate easier to turn. Some of the chambers are also filled with water as ballast.

The closed chambers are hard to keep tight and somewhat inaccessible. For this reason in some of the latest designs, such as the Cascade Locks on the Columbia River and the Plaquemine Locks in Louisiana, both built by the U. S. Government, they have been omitted and the gates built with a single skin only.

In the beginning the actual design, the first point to be settled is the rise of the sill which fixes the angle which the gates make with the axis of the lock. The rise varies from $\frac{1}{3}$ to $\frac{1}{6}$ of the width in various locks, but a rise of $\frac{1}{5}$ is perhaps the best, being as economical as a greater rise.

The next point to be considered is the proper outline of the horizontals. These are almost always plate girders. They may have a girder shape or else follow the lines of an arch the medial line of which is a circular curve through the centre of the quoin and mitre posts.

Each horizontal is in equilibrium under three external forces, viz.: the water pressure, which is uniform and normal to the face of the gate, the reaction of the other leaf which is at right angles to the axis of the lock and the reaction of the masonry at the quoin. These two reactions are equal and make the same angle with a line connecting the centre of pressure at the quoin and mitre posts.

If the gate consisted of a linear arch without thickness, a circle would be the true line of equilibrium for the forces acting on it and the arch would be in pure compression and hence the most economical shape. On these theoretical grounds, it has generally been held that an arch gate of circular shape is necessarily the most economical. This has been stated by many different writers for 50 years back and the proposition has been re-inforced by many intricate calculations involving the use of the higher mathematics.

As a matter of fact, the gates are never linear arches but must be built as curved beams which are rarely less than 3 feet in thickness so that the surface submitted to the water pressure is not identical with the curved axis of the horizontal girder. Furthermore the center of contact or pressure where one leaf presses against the other at the mitre post is rarely exactly on the medial line, but on the contrary varies considerably on either side. This difference of position is due both to unavoidable inaccuracy in fitting and material and also to the change in the length of the gate leaves at different times owing to variations in temperature. As a result of this the circular arch is never in pure compression but also subject to considerable cross-bending. Besides this in proportioning engineering structures many practical considerations, such as the minimum thickness of metal, etc., that may be used must be taken into account, so that any general theoretical deduction loses still more in value.

The only reliable method of comparison for different shapes consists in a series of estimates based on actual detailed designs. By means of several extended estimates of this kind the writer has satisfied himself that at least for locks up to 80 feet in width, the circular arched gate is no more economical than the straight or girder shape, while it has many practical disadvantages.

The dimensions of the web and flanges in any given girder are to be determined by the rules commonly used where there is a combination of compressive and bending stresses.

Another interesting question is the distribution of the total water pressure over the different horizontal girders. The total amount of this pressure for the whole gate is perfectly determinate. In case the horizontal girders were connected by a flexible sheathing, the distribution would be equally simple, each girder getting exactly the load due to its head below water level. As actually built the girrders are connected by sheathing that has some stiffness and by vertical posts that have much rigidity. Furthermore, the bottom of the gate fits more or less closely against a solid sill. The stiff vertical members modify the distribution of the load over the different horizontals, even when there is no contact on the bottom sill and still more when there is contact so that the verticals carry some of the water pressure to the bottom sill. The result is that the upper part of the gate is more fully loaded, while the lower horizontals are proportionately relieved.

Some interesting experiments on models made by M. Chevalier in France in 1850, illustrate this point very beautifully. The mathematical statement of these complex stresses has also been attempted by several French engineers, but their methods are extremely intricate and the results while indicating correct values, hardly merit extreme confidence.

The method of "Least Work" for solving indeterminate stresses has been applied by the writer to this question with results that agree satisfactorily with some measurements he has made during the past year in the deflections of large gates.

French Engineers commonly design the lower girders of their gates in accordance with the formulæ referred to above, assuming simultaneous contact of the mitre post and sill at all times, while in England it is usual to proportion each girder for its full hydrostatic head. As the close fitting at the sill is likely to fail at times, the English practice seems the safer one, though the upper part of the gate should be strengthened rather more than is customary in some of the English gates.

The details of construction in all parts of the gate will, of course, vary according to the individual judgment of the engineer in charge.

Many otherwise good gates are unnecessarily complex in construction, showing a lack of familiarity with shop practice on the part of their designers.

In lock-gates, which are machines rather than structures, facility of operation and freedom from breakdowns are far more important than first cost. At the same time, a gate that is simple in detail is also likely to be satisfactory in daily use.

MACHINERY FOR OPENING AND SHUTTING THE GATES.

The methods used for opening and shutting the gates can only be briefly referred to. In large modern locks the machinery is always operated by power in order to shorten the time required. The prime movers are generally turbine wheels operated by the water in the canal at a head equal to the lift of the lock. The power thus generated is transmitted to the mechanism for moving the gate by water under pressure, by compressed air or by electricity. In the past, water under pressures varying from 100 to 800 lbs. has been generally used. Machinery of this kind was first designed by Sir William Armstrong for English harbor locks, and includes the use of his well-known accumulator. Most English plants have been constructed by this firm and designers in other countries have generally used very similar forms. The water under pressure moves reciprocating pistons to which the cables are attached, or else rotary engines, usually with three cylinders, are used.

The turning of the gates is generally effected by steel cables or chains which are attached close to the mitre post near the bottom of the gate. One cable serves for opening and another for closing. The cables are brought to the engines on the top of the lock walls, through tunnels built in the masonry. The details of the attachment and general arrangement differ in various designs, but it is usual to have an independent engine on each side wall.

Although cables and chains have worked very satisfactorily, they have some disadvantages and in several recent locks other appliances for opening and shutting the gates have been adopted, thus in the new locks at Barry, in England, a stiff strut is used which is attached to the gate above the surface of the water and serves both to open and shut it. One end of this strut connects directly to a plunger that moves in an hydraulic cylinder. This cylinder oscillates on a double axis which is placed in a recess built in the wall approximately at right angles to the face of the wall. In the North Sea-Baltic Canal and also at the west end of the Amsterdam Canal a similar arrangement is used, but the strut is not directly moved by hydraulic power but carries a rack that connects with geared spur wheels.

Quite recently electric motors have been substituted for water pressure engines and the use of this power is likely to become general.

Hydraulic machinery in cold climates is always likely to give trouble and in some instances it is necessary to use oil in place of water during the Spring and Fall before it becomes necessary to cease operations entirely. Besides this, the transmission of power by pressure pipes to distant parts of the large lock involves expensive construction and repairs are frequently needed. The use of the electric current would seem to obviate all these difficulties. In the Canadian lock at Sault Ste. Marie, electric motors are used for opening and shutting the gates as well as operating the large valves in the culverts. The operation of this machinery is entirely satisfactory, although it seems to be rather complicated.

Electric power has also been adopted for the gates of the new lock at Ymuiden on the Amsterdam Ship Canal, as a result of an extended series of experiments. We may expect that in the future most of the new locks will be operated as well as lighted by electricity.

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